Making integrated circuits

2012-03-14

Carsten Wulff

Outline

- Compulsory introduction: who am I, what have I done, and what do I do, where do I work, what to they do….
- Circuit elements
- Processing
- Layout
- Schematics
- Advice for electronics students

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Who am I?

- Carsten Wulff
- Born Friday 13. August 1976
- Senior R & D engineer, wireless department at Nordic Semiconductor
- Married with three kids
- Graduated from NTNU 2002 (Programmable analog integrated circuit with TOC, 0.6um AMS)
- Ph.D from NTNU in 2008 (Efficient ADCs in nano-scale CMOS technology, 90nm ST)
- Fortunate to spend a year at University of Toronto (2006-2007) during my Ph.D
- http://www.scribd.com/carstenwulff
- http://www.wulff.no/carsten

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Electronics research

Research takes time

Software design

Acoustics

Signal processing

Computer design

Radio Systems

Circuit- and systems design

Electro-optics

Electronic Devices and Materials

Time to market: Months — Years — Decades

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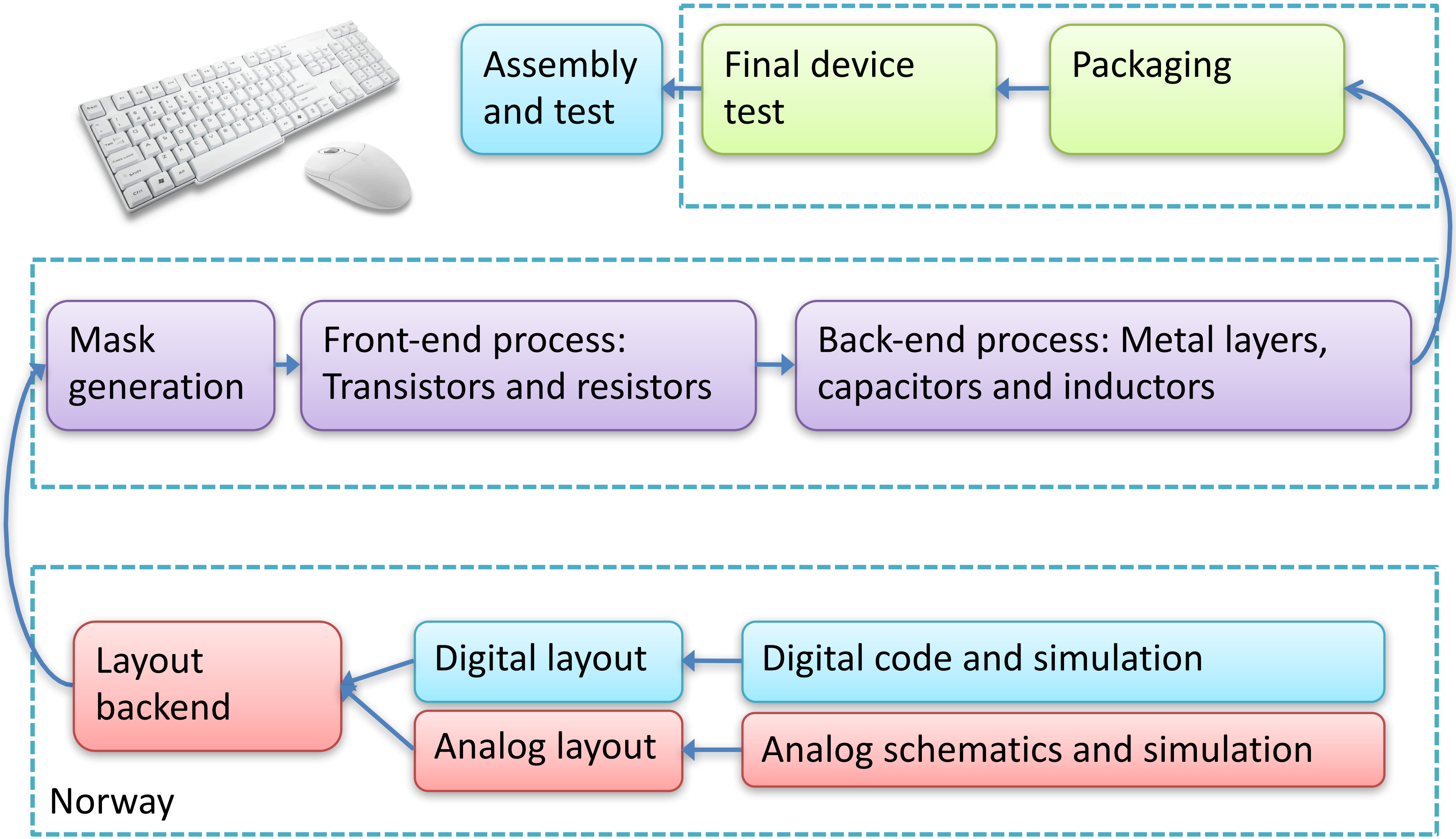
The story



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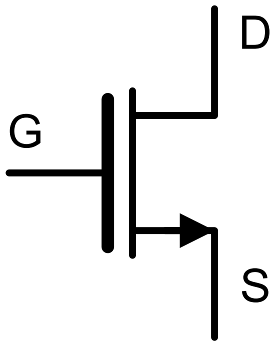
Circuit elements

Transistor – The workhorse of ICs

- An extremely complicated device, but it's possible to make some assumptions



The accurate equation

$$I_D = f(W, L, \mu_n, C_{ox}, \ldots, V_{GS,} V_{DS}, \ldots) \text{ 284 parameters in BSIM 4.5}$$

The equation used for hand calculation in analog circuits

$$I_D \propto (V_{GS} - V_{th})^2$$

The equation sufficient for most digital designs

$$I_D \propto \begin{cases} high, \text{ if } V_{GS} > V_{TH} \\ 0, \text{ if } V_{GS} < V_{TH} \end{cases}$$

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Parameters for one transistor in BSIM 4.5

.MODEL N1 NMOS LEVEL=14 VERSION=4.5.0 BINUNIT=1 PARAMCHK=1 MOBMOD=0 CAPMOD=2 IGCMOD=1 IGBMOD=1 GEOMOD=1 DIOMOD=1 RDSMOD=0 RBODYMOD=0 RGATEMOD=3 PERMOD=1 ACNQSMOD=0 TRNQSMOD=0 TEMPMOD=0 TNOM=27 **TOXE=1.8E-009** TOXP=10E-010 TOXM=1.8E-009 DTOX=8E-10 EPSROX=3.9 WINT=5E-009 LINT=1E-009 LL=0 WL=0 LLN=1 WLN=1 LW=0 WW=0 LWN=1 WWN=1 LWL=0 WWL=0 XPART=0 TOXREF=1.4E-009 SAREF=5E-6 SBREF=5E-6 WLOD=2E-6 KU0=-4E-6 KVSAT=0.2 KVTH0=-2E-8 TKU0=0.0 LLODKU0=1.1 WLODKU0=1.1 LLODVTH=1.0 WLODVTH=1.0 LKU0=1E-6 WKU0=1E-6 PKU0=0.0 LKVTH0=1.1E-6 WKVTH0=1.1E-6 PKVTH0=0.0 STK2=0.0 LODK2=1.0 STETA0=0.0 LODETA0=1.0 LAMBDA=4E-10 VSAT=1.1E 005 VTL=2.0E5 XN=6.0 LC=5E-9 RNOIA=0.577 RNOIB=0.37 LINTNOI=1E-009 WPEMOD=0 WEB=0.0 WEC=0.0 KVTH0WE=1.0 K2WE=1.0 KU0WE=1.0 SCREF=5.0E-6 TVOFF=0.0 TVFBSDOFF=0.0 **VTH0=0.25** K1=0.35 K2=0.05 K3=0 K3B=0 W0=2.5E-006 DVT0=1.8 DVT1=0.52 DVT2=-0.032 DVT0W=0 DVT1W=0 DVT2W=0 DSUB=2 MINV=0.05 VOFFL=0 DVTP0=1E-007 DVTP1=0.05 LPE0=5.75E-008 LPEB=2.3E-010 XJ=2E-008 NGATE=5E 020 NDEP=2.8E 018 NSD=1E 020 PHIN=0 CDSC=0.0002 CDSCB=0 CDSCD=0 CIT=0 VOFF=-0.15 NFACTOR=1.2 ETA0=0.05 ETAB=0 UC=-3E-011 VFB=-0.55 **U0=0.032** UA=5.0E-011 UB=3.5E-018 A0=2 AGS=1E-020 A1=0 A2=1 B0=-1E-020 B1=0 KETA=0.04 DWG=0 DWB=0 PCLM=0.08 PDIBLC1=0.028 PDIBLC2=0.022 PDIBLCB=-0.005 DROUT=0.45 PVAG=1E-020 DELTA=0.01 PSCBE1=8.14E 008 PSCBE2=5E-008 RSH=0 RDSW=0 RSW=0 RDW=0 FPROUT=0.2 PDITS=0.2 PDITSD=0.23 PDITSL=2.3E 006 RSH=0 RDSW=50 RSW=150 RDW=150 RDSWMIN=0 RDWMIN=0 RSWMIN=0 PRWG=0 PRWB=6.8E-011 WR=1 ALPHA0=0.074 ALPHA1=0.005 BETA0=30 AGIDL=0.0002 BGIDL=2.1E 009 CGIDL=0.0002 EGIDL=0.8 AIGBACC=0.012 BIGBACC=0.0028 CIGBACC=0.002 NIGBACC=1 AIGBINV=0.014 BIGBINV=0.004 CIGBINV=0.004 EIGBINV=1.1 NIGBINV=3 AIGC=0.012 BIGC=0.0028 CIGC=0.002 AIGSD=0.012 BIGSD=0.0028 CIGSD=0.002 NIGC=1 POXEDGE=1 PIGCD=1 NTOX=1 VFBSDOFF=0.0 XRCRG1=12 XRCRG2=5 CGSO=6.238E-010 CGDO=6.238E-010 CGBO=2.56E-011 CGDL=2.495E-10 CGSL=2.495E-10 CKAPPAS=0.03 CKAPPAD=0.03 ACDE=1 MOIN=15 NOFF=0.9 VOFFCV=0.02 KT1=-0.37 KT1L=0.0 KT2=-0.042 UTE=-1.5 UA1=1E-009 UB1=-3.5E-019 UC1=0 PRT=0 AT=53000 FNOIMOD=1 TNOIMOD=0 JSS=0.0001 JSWS=1E-011 JSWGS=1E-010 NJS=1 IJTHSFWD=0.01 IJTHSREV=0.001 BVS=10 XJBVS=1 JSD=0.0001 JSWD=1E-011 JSWGD=1E-010 NJD=1 IJTHDFWD=0.01 IJTHDREV=0.001 BVD=10 XJBVD=1 PBS=1 CJS=0.0005 MJS=0.5 PBSWS=1 CJSWS=5E-010 MJSWS=0.33 PBSWGS=1 CJSWGS=3E-010 MJSWGS=0.33 PBD=1 CJD=0.0005 MJD=0.5 PBSWD=1 CJSWD=5E-010 MJSWD=0.33 PBSWGD=1 CJSWGD=5E-010 MJSWGD=0.33 TPB=0.005 TCJ=0.001 TPBSW=0.005 TCJSW=0.001 TPBSWG=0.005 TCJSWG=0.001 XTIS=3 XTID=3 DMCG=0E-006 DMCI=0E-006 DMDG=0E-006 DMCGT=0E-007 DWJ=0.0E-008 XGW=0E-007 XGL=0E-008 RSHG=0.4 GBMIN=1E-010 RBPB=5 RBPD=15 RBPS=15 RBDB=15 RBSB=15 NGCON=1 JTSS=1E-4 JTSD=1E-4 JTSSWS=1E-10 JTSSWD=1E-10 JTSSWGS=1E-7 JTSSWGD=1E-7 NJTS=20.0 NJTSSW=20 NJTSSWG=6 VTSS=10 VTSD=10 VTSSWS=10 VTSSWD=10 VTSSWGS=2 VTSSWGD=2 XTSS=0.02 XTSD=0.02 XTSSWS=0.02 XTSSWD=0.02 XTSSWGS=0.02 XTSSWGD=0.02

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_{th}\right)^2$$

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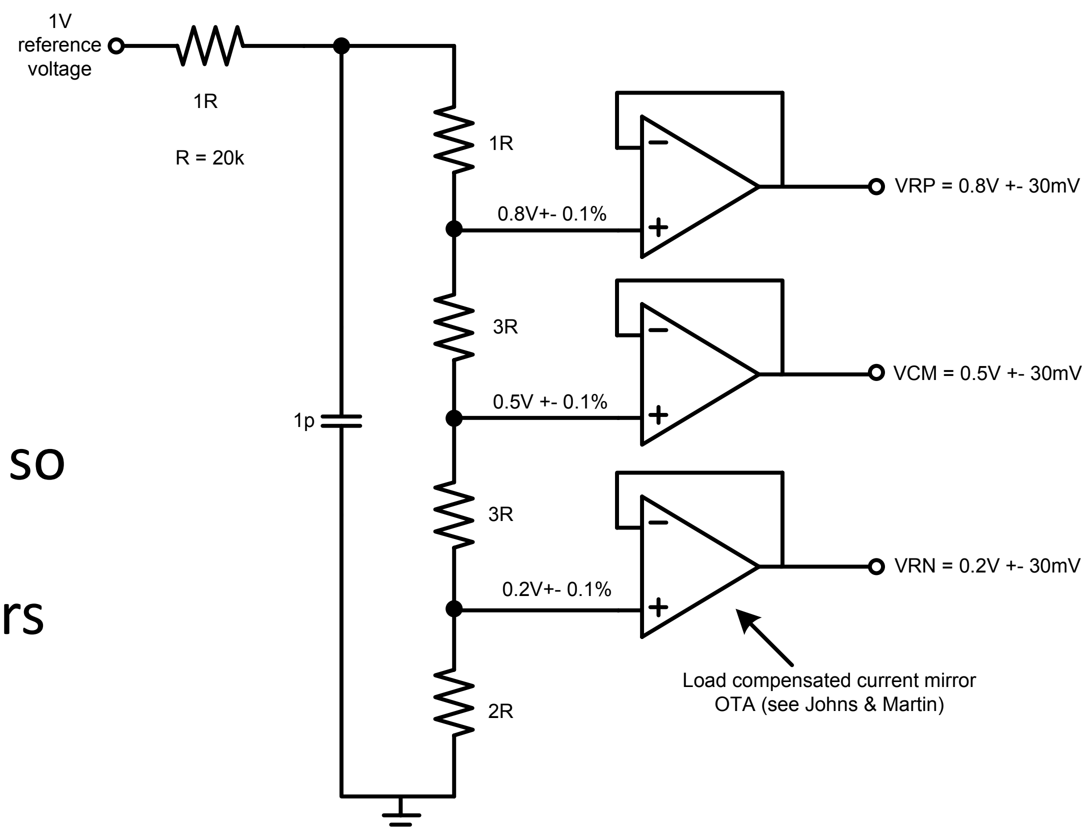
Integrated resistor – Master of ratios

- Most of the time a simple device

V = I R

- Very good matching between two resistors, so we can make very accurate voltage dividers



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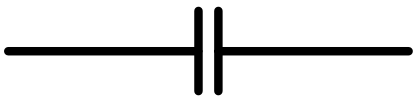
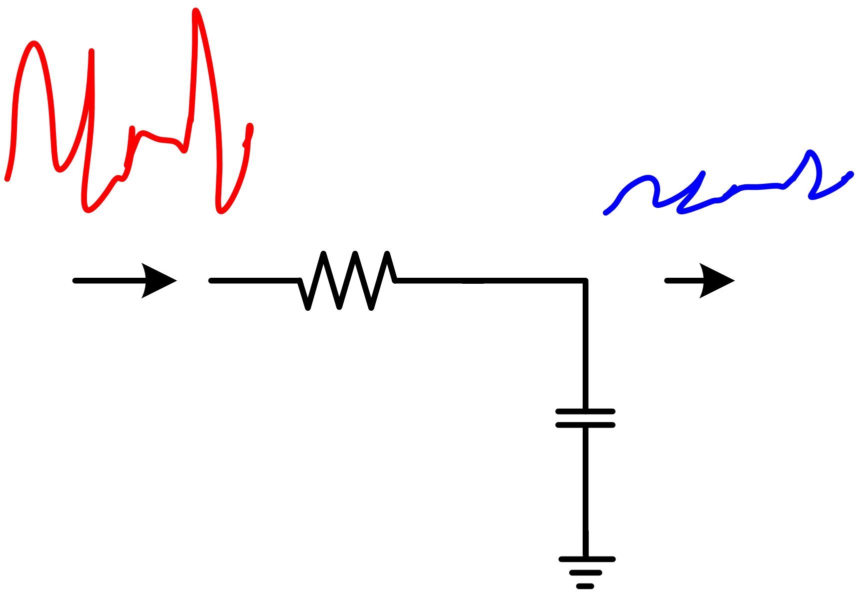
Integrated capacitor – Master of silence

- Not to hard either



i = C dv/dt

- Perfect for silencing a noisy power supply



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Integrated inductor – Master of radio frequencies

- Principle is simple, not so easy to integrate on chip

$$V = L \; di/dt$$

- Used in sine wave generators, and radio frequency circuits

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Processing – Making an integrated circuit

Search terms: integrated circuit processing

The raw materials

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122													carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086		sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723		arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

- A chip is made layer by layer by adding dopants, metal, insulators and conductors

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The wafer – the fundamental building block

http://www.tomshardware.com/reviews/semiconductor-production-101,1590-3.html

- Ingot = An ultra pure, single crystal of silicon
- Wafer = A very thin slice of an ingot, used as the first layer in processing

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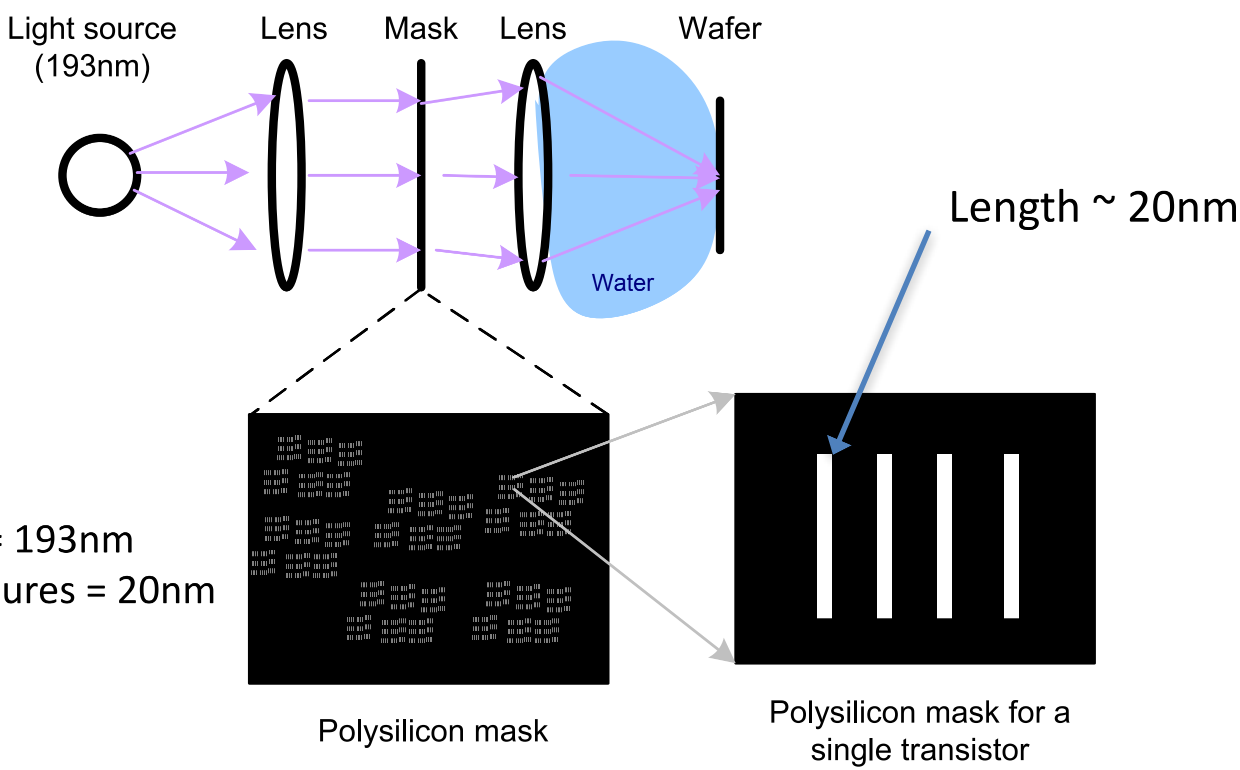
Photolithography



Wavelength of light = 193nm
Size of minimum features = 20nm

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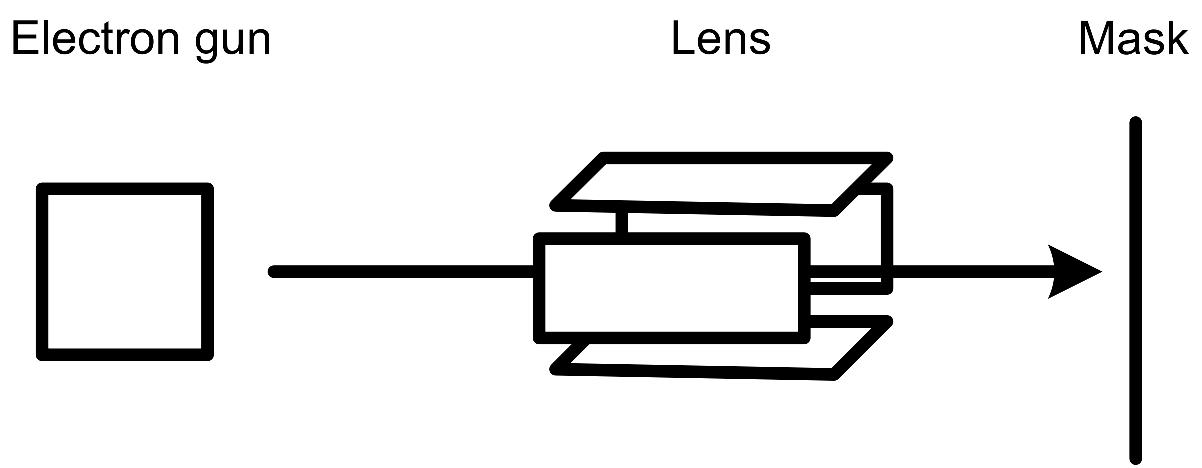
Mask generation



- Extremely expensive
- Must have higher accuracy that what we want to develop

Minimum feature	Mask cost NOK
180nm	600 000
65nm	6 000 000
28nm	30 000 000

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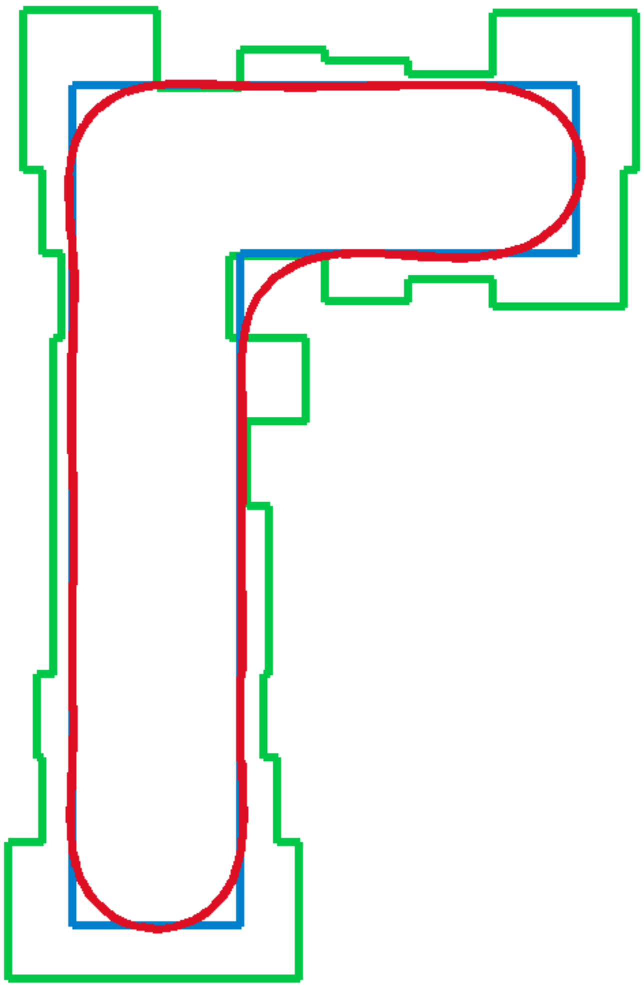
Optical proximity correction (What you see is not what you get)



- The wavelength of the developing light is larger than minimum features (193nm > 20nm)
- Diffraction patterns affect the light intensity on the photo-resist
- Extensive calculations need to calculate how the mask should look to compensate for diffraction and processing inaccuracies

Blue = Pattern we draw in our CAD programs

Green = How the mask actually looks

Red = Pattern on chip

http://upload.wikimedia.org/wikipedia/en/6/65/Optical_proximity_correction.png

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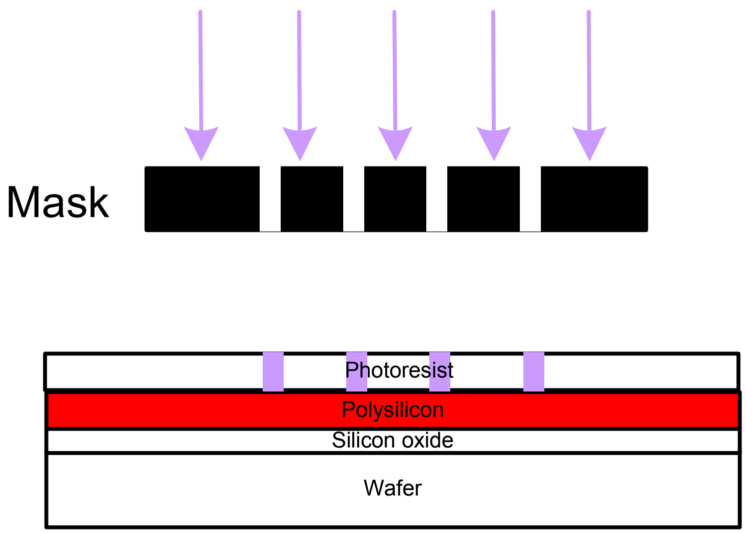
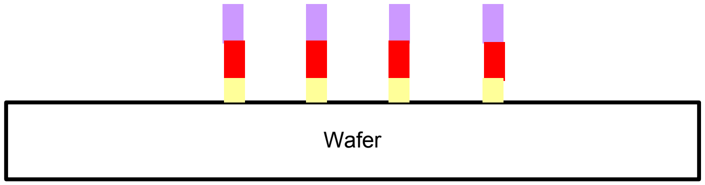
Search terms: photoresist lithography, reactive ion etching

Photo resist and development



1) Expose photoresist



2) Remove photoresist and etch polysilicon

Toolbox
- Negative and positive photoresist
- Doping, etching, electroplating, vapor deposition

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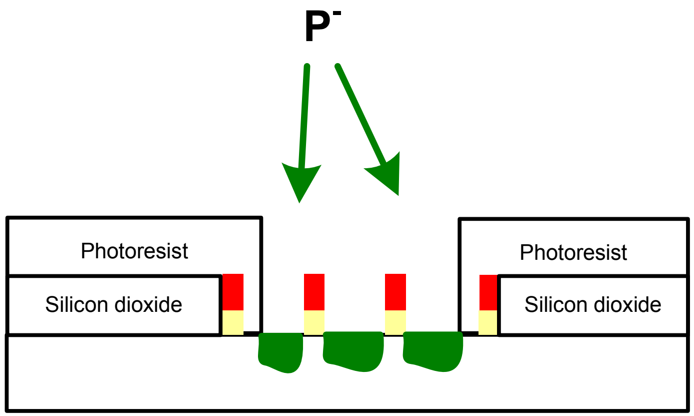
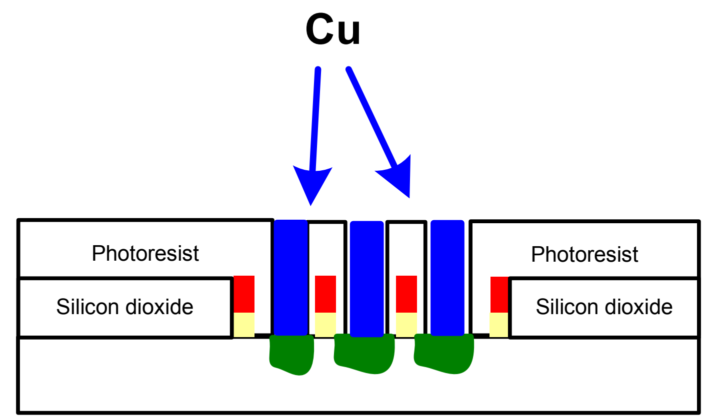
Search terms: dual damascene copper

Doping and metal



3) Add doping



4) Add metal

- Dopants change electrical properties of the silicon substrate
- Metal is added to wire up the circuit. In most processes the metal is copper.
- Up to nine metal layers in advanced processes

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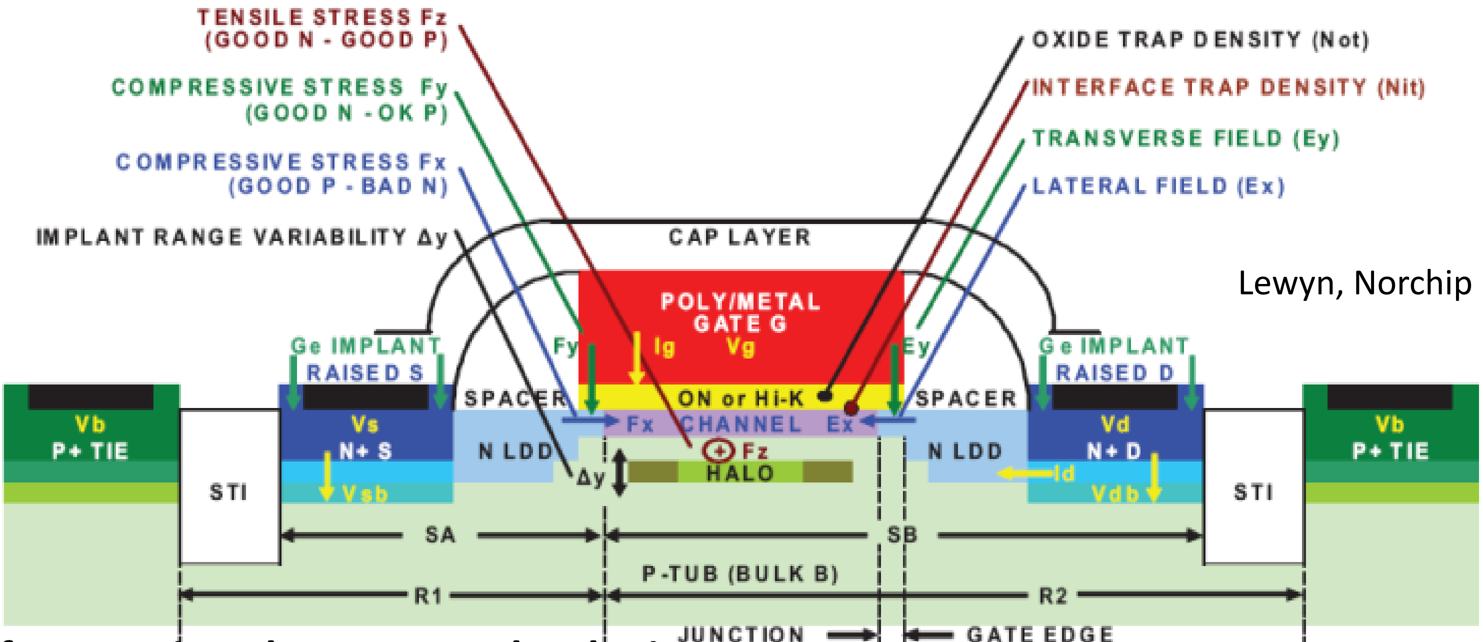
Nanoscale transistor



Lewyn, Norchip 2009

New features in sub 100nm technologies:

- Stress is actively used to increase mobility
- Very thin oxide, reduced power supply to keep vertical field in check
- Halo implant that increases drain-source conductance at longer channel lengths
- Hot carrier effects
- Stress from the STI (shallow trench isolation)
- Proximity to well edge
- Lithography issues since the minimum dimensions are less than the wavelength used to expose the photoresist (λ=193nm)

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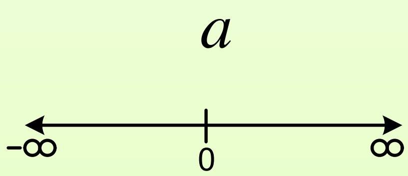
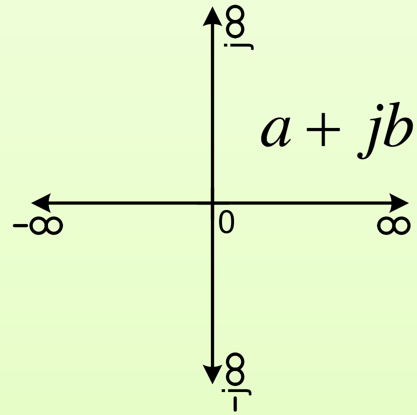
We digress: Complex math



Real numbers

$$\sqrt{-1} = i = j$$



Complex numbers

$$Y(t) = I(t) + jQ(t)$$

Our radio uses a complex reciever (one path for I and one for Q), so you need to understand complex mathematics

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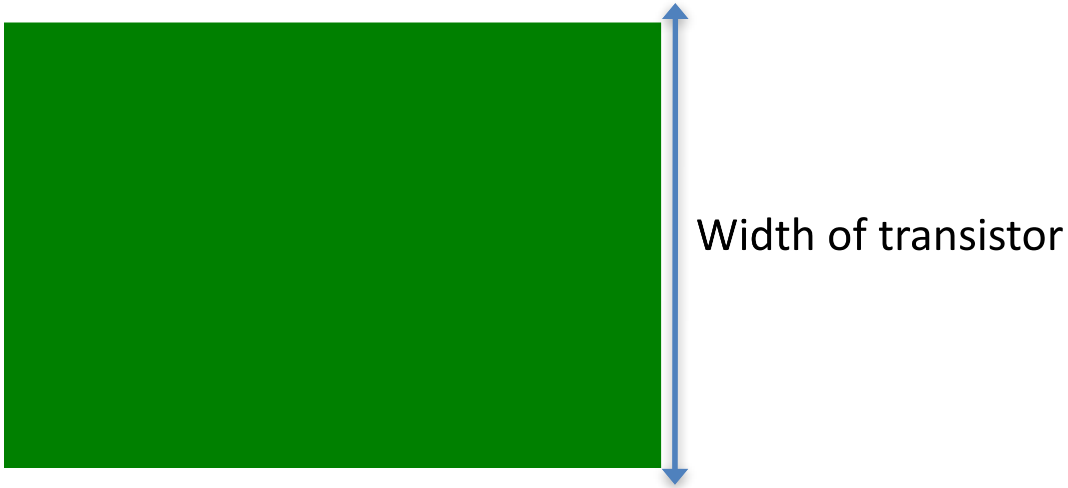
Layout

Let's make a transistor

Diffusion



- Marks the boundry of the transistor
- Defines the width of the transistor

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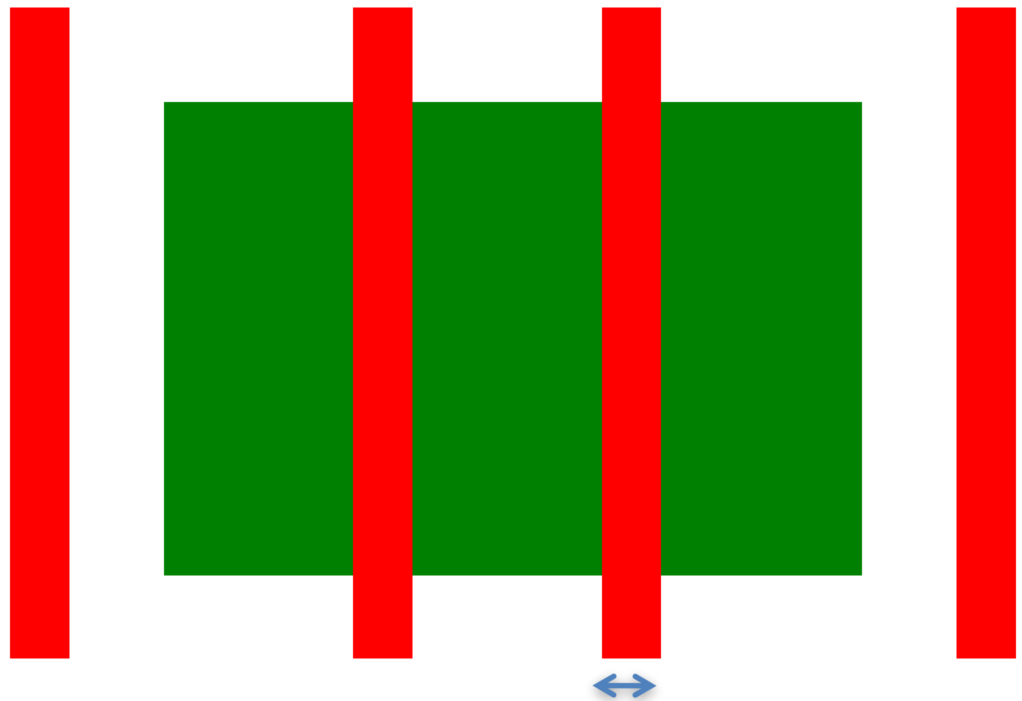
Polysilicon



- The intersection of diffusion and polysilicon defines the transistor
- Polysilicon is the gate of the transistor, and sets the length

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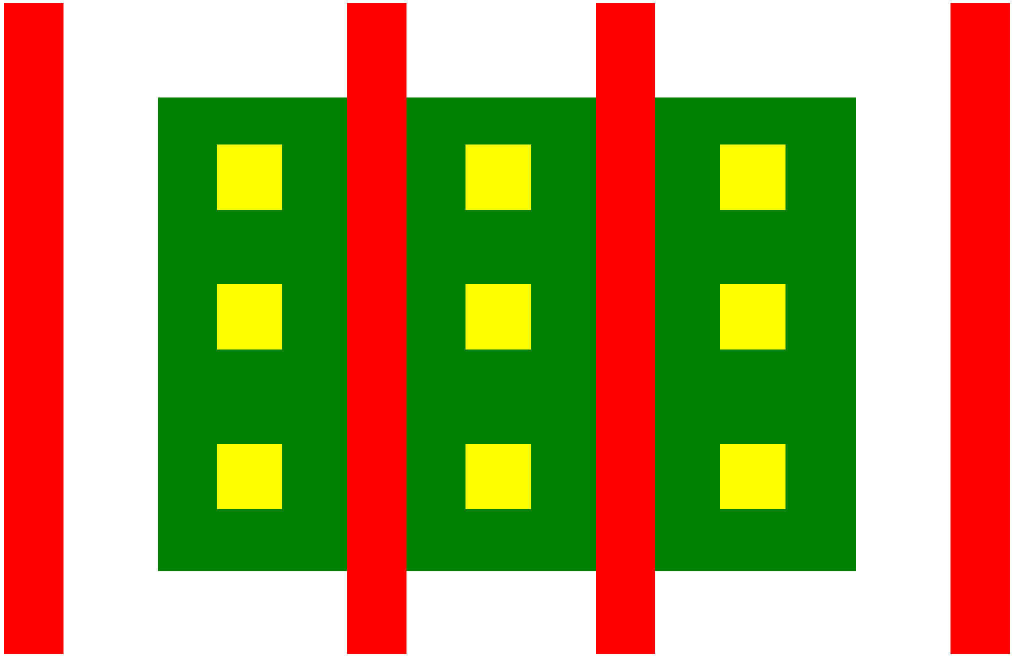
Contacts



- Contacts are needed to connect between metal and diffusion

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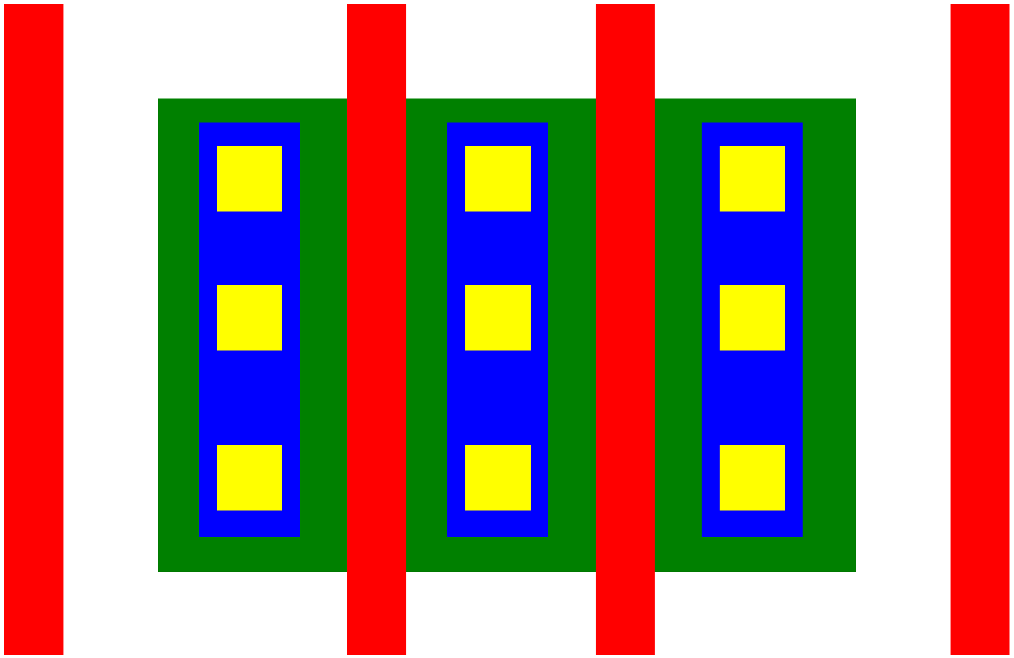
Metal



- Metal is used to connect one transistor to another

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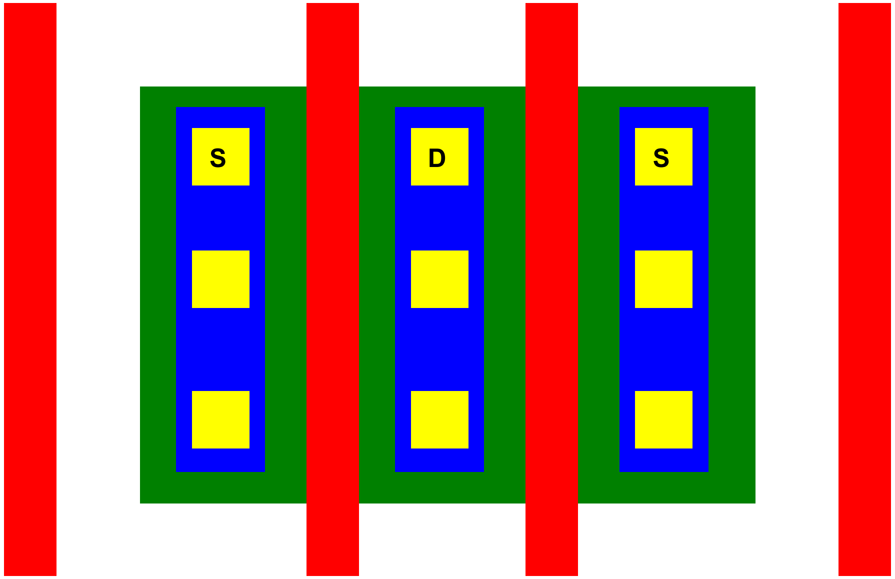
Transistor layout rules



Rule	Why
Always use two fingers	Transistor parameters change with current direction
Always run all gates in same direction	Stress in X and Y direction affect transistor differently
Always have dummy poly	Better poly control during processing
Always have larger than minimum length of diffusion	Less stress from shallow trench isolation
Always place transistors far from well edge	Reduce mismatch in threshold voltage
Be careful with metal routing across transistors	Metal changes the stress in the channel

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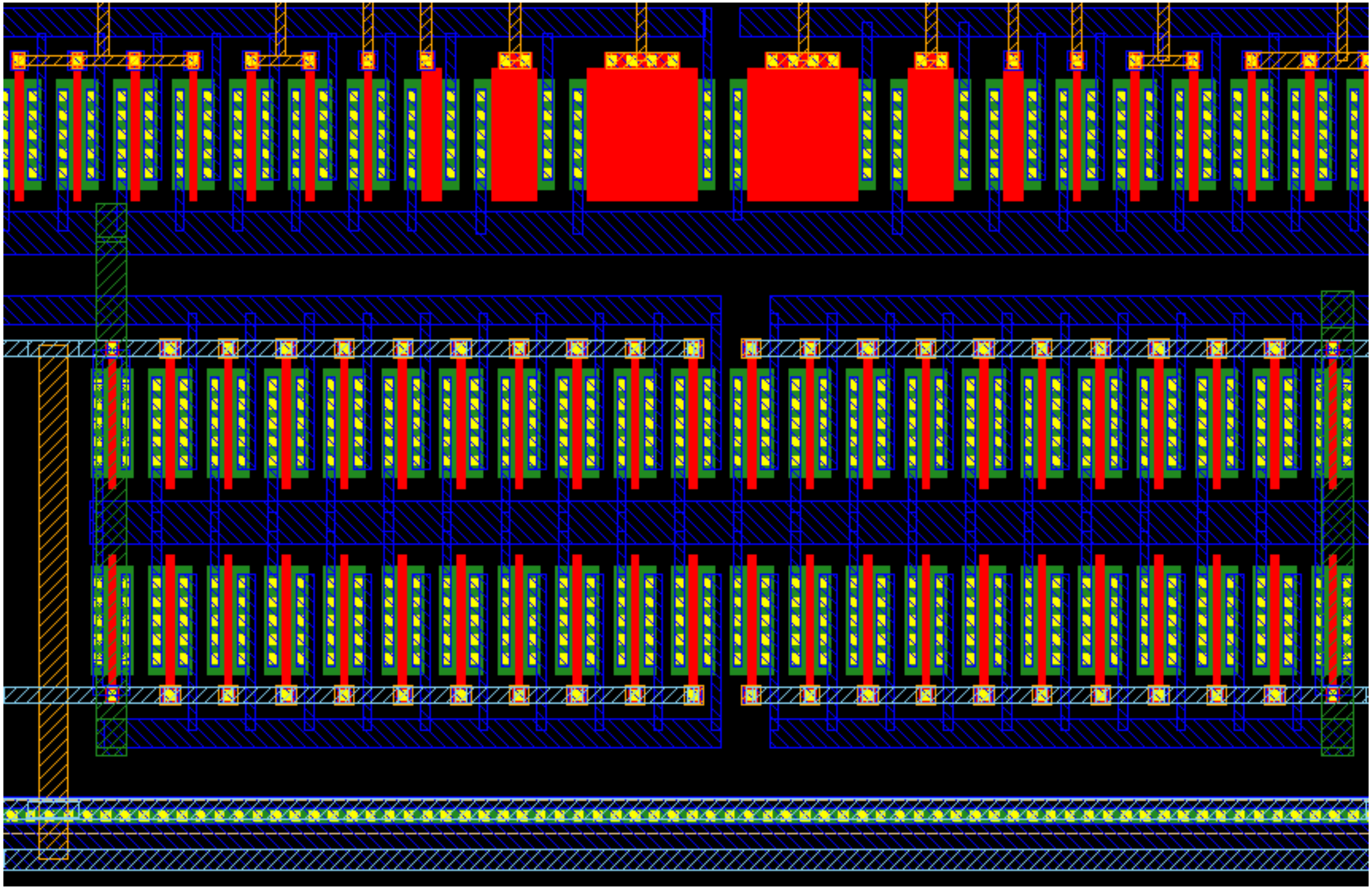
Layout of an opamp



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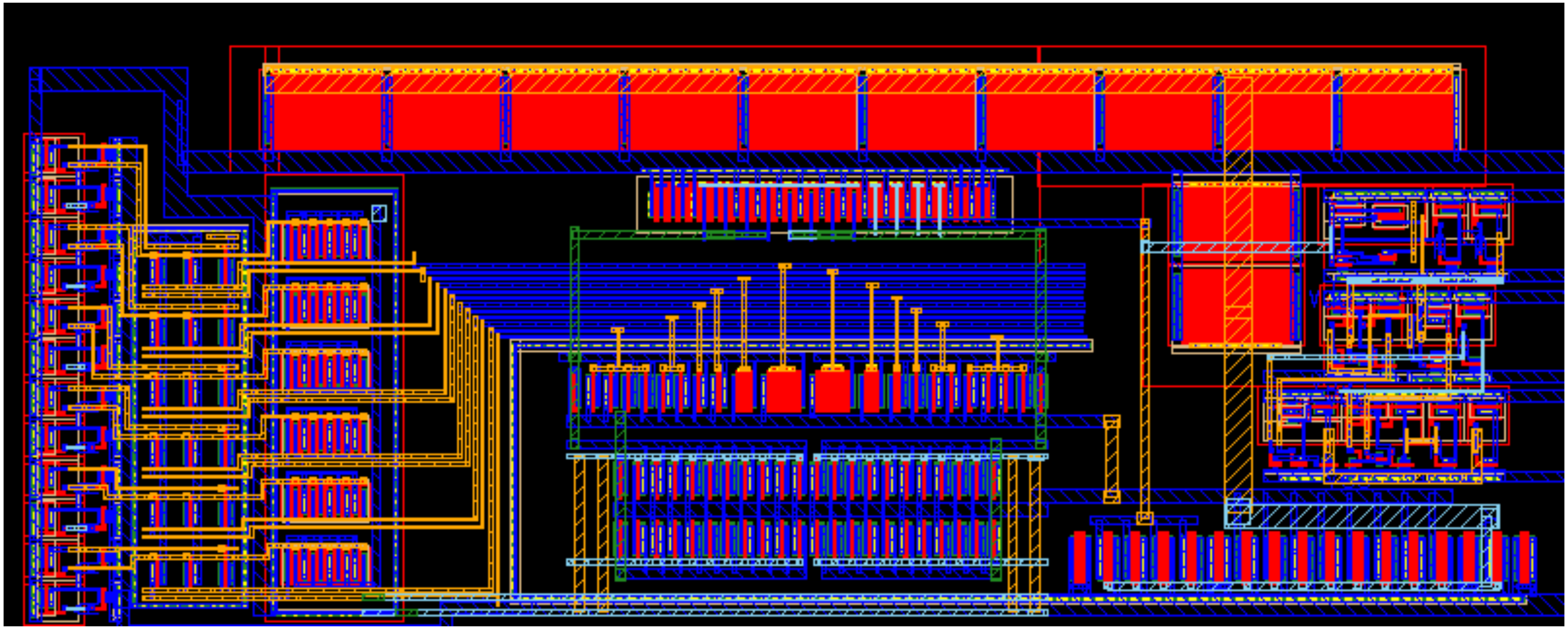
Layout of opamp



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Layout of an ADC

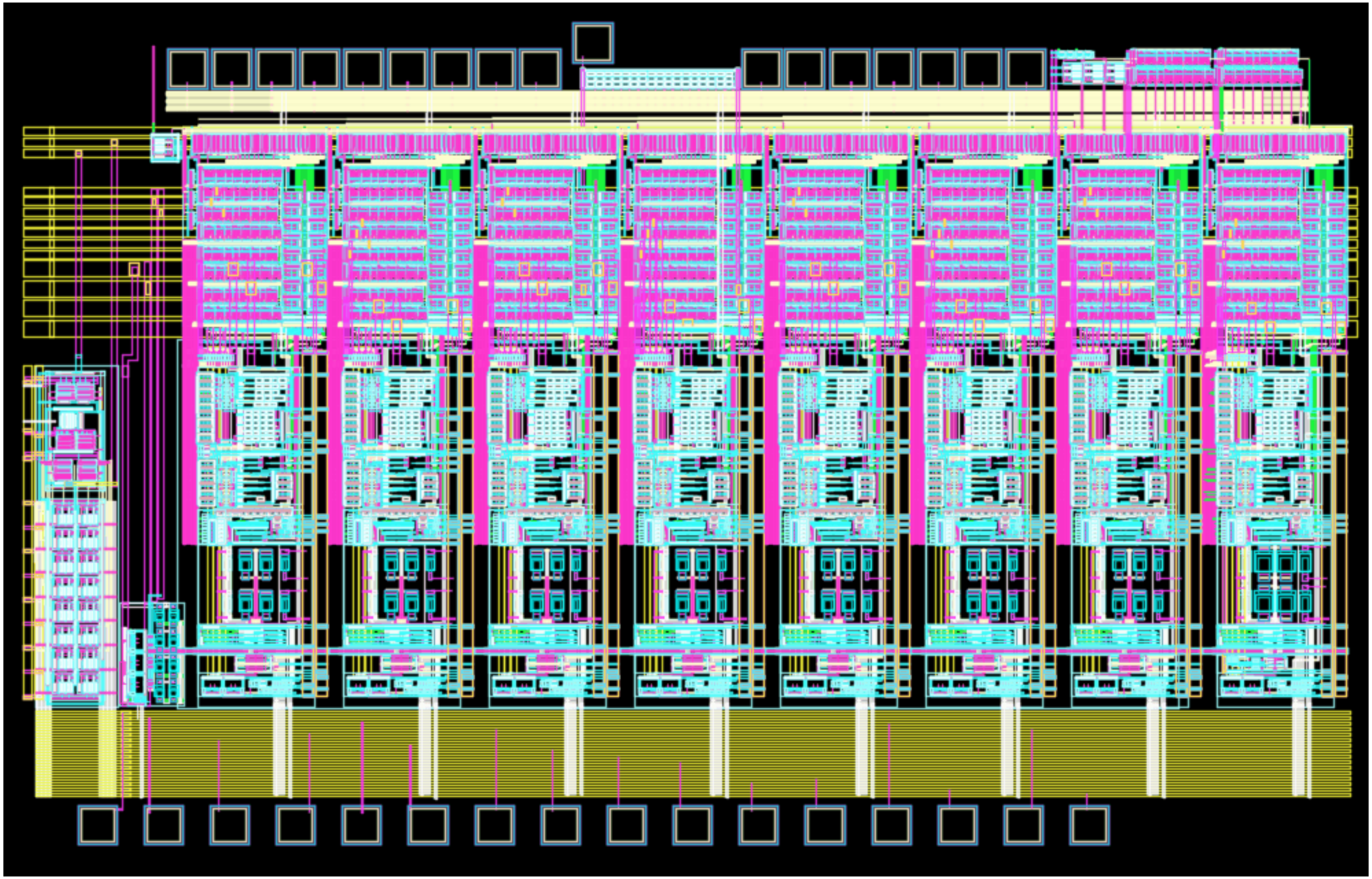

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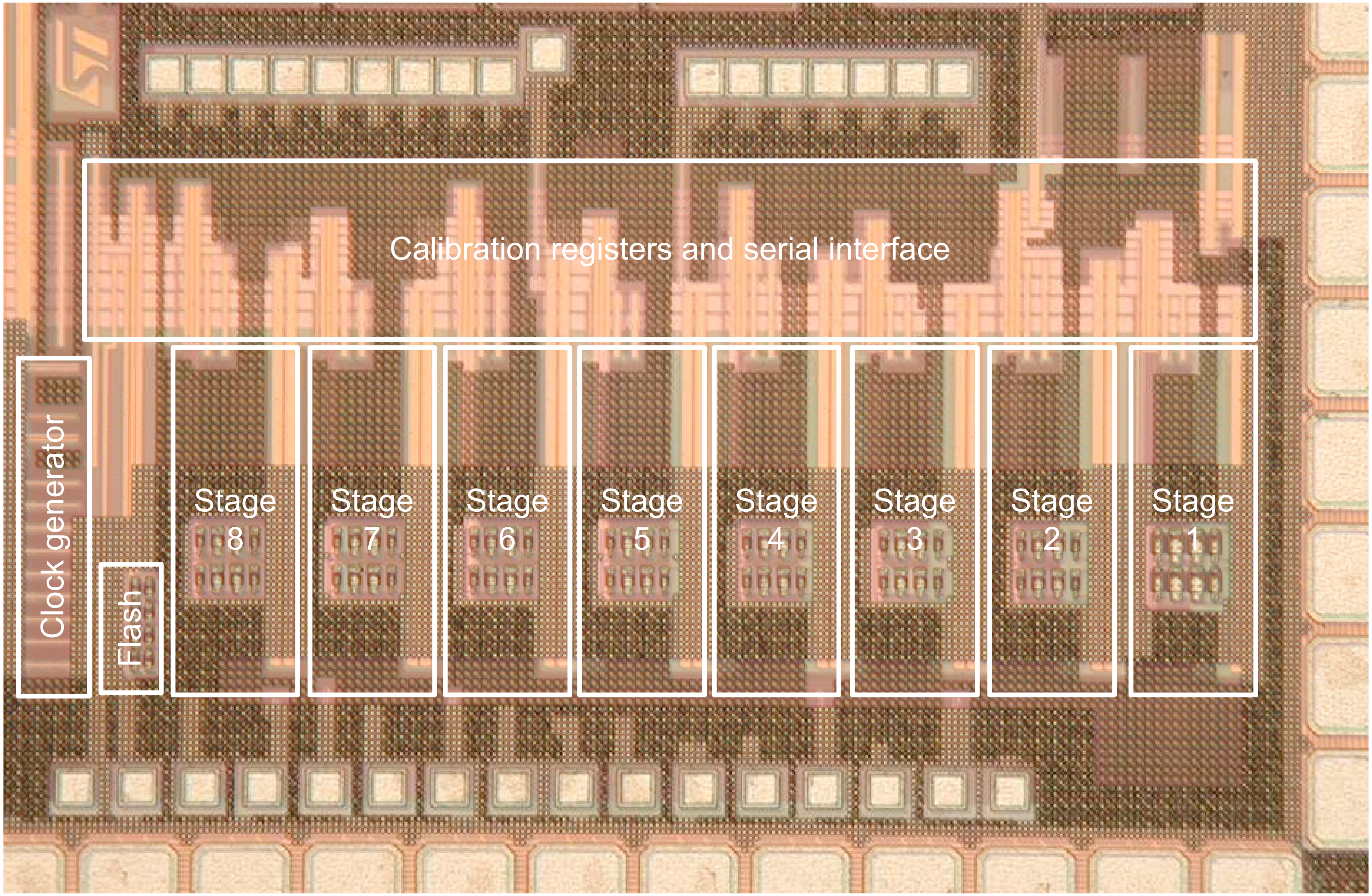
Image of an ADC



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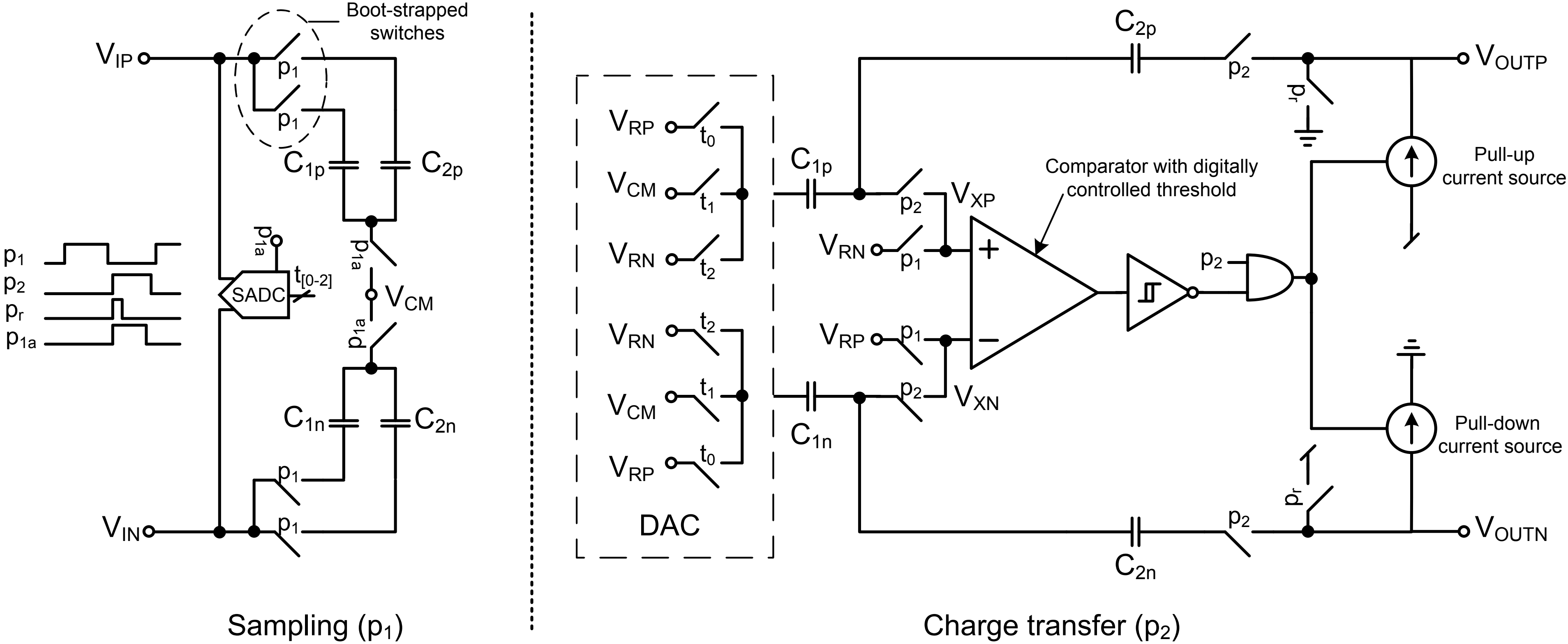
Schematics

Typical block diagram



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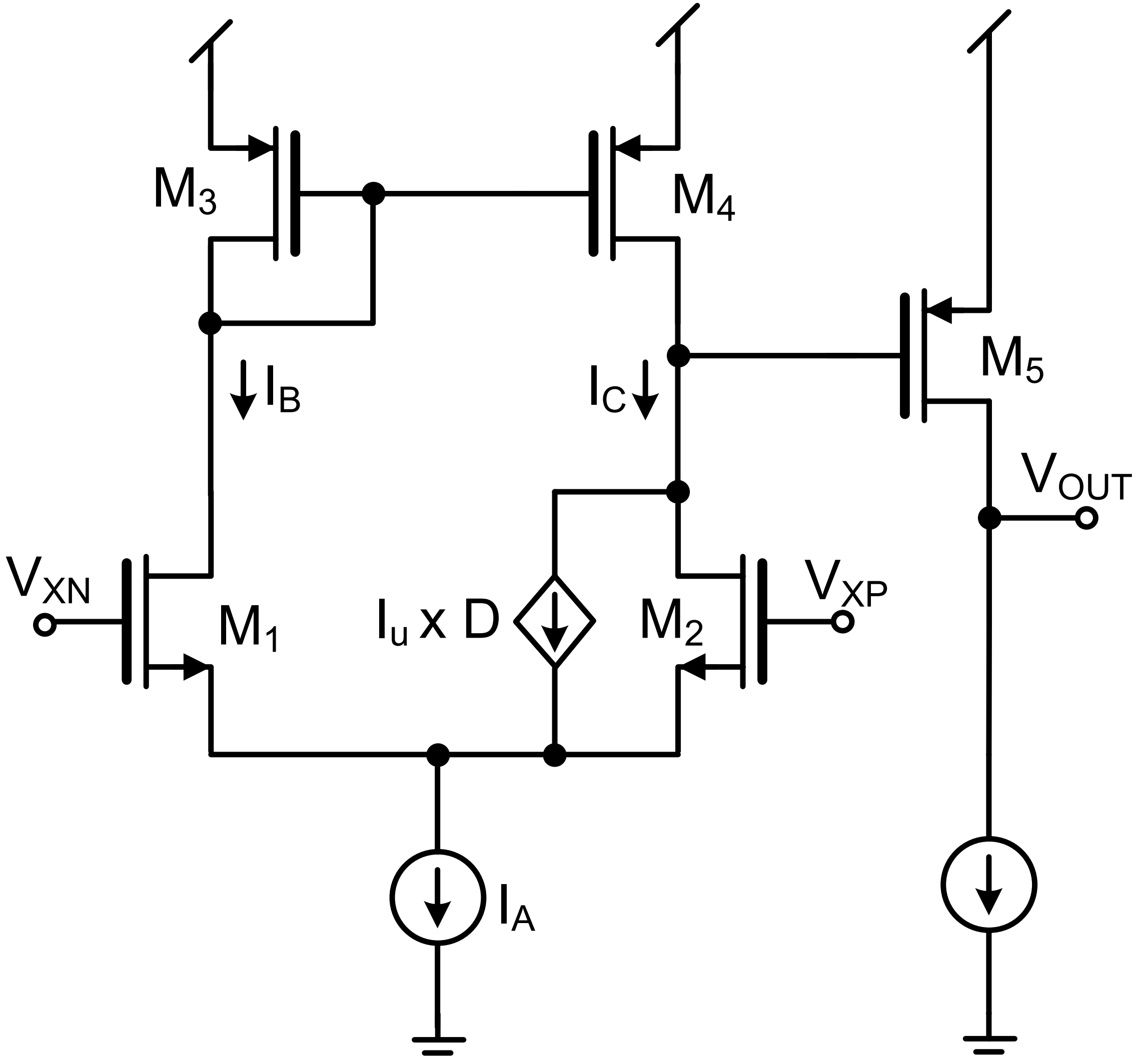
Opamp schematic in Visio



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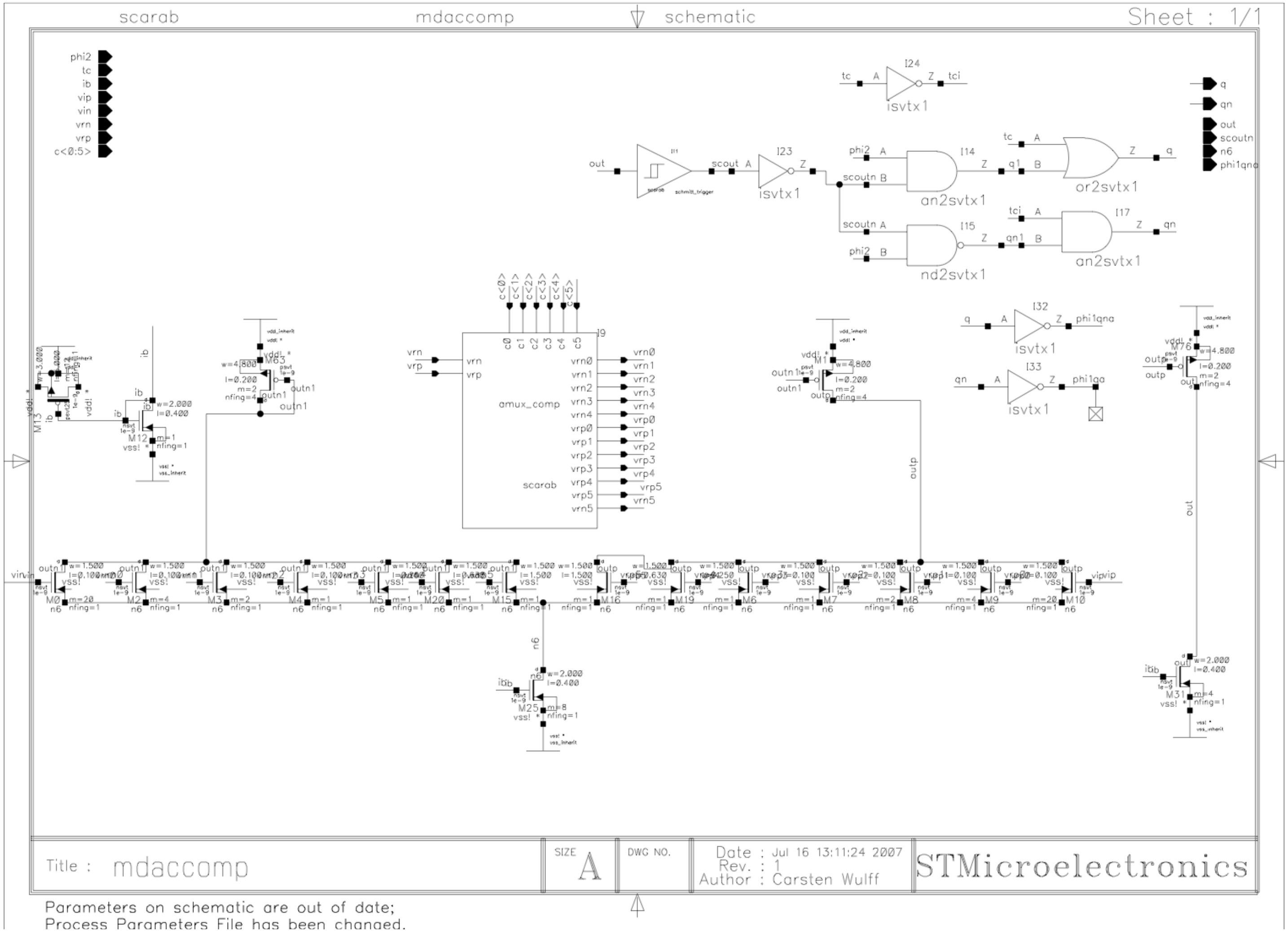
Opamp schematic in Cadence



http://www.wulff.no/carsten/lib/exe/fetch.php/carsten/pub/scarab.pdf

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Topics not covered

- Simulation, corner verification, monte-carlo simulation
- Digital design (Verilog)
- System level design (Matlab)
- Project management
- Lab testing
- Writing documentation

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Divide and conquer

- Break complex stuff down into smaller pieces
- Ignore the difficult stuff, and try to get an approximate understanding, then add inn the difficult stuff
- Don’t be afraid if something is difficult
- Don’t think your stupid and won’t be able to understand
- Don’t think that everybody else is smarter than you

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When you don’t understand

- Ask someone
- Don’t be afraid to show that you don’t know something, not knowing is OK (except on the exam, and in a job interview)
- Use wikipedia

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Know your assumptions

- Assumption is your friend
- Assumption is your worst enemy
- Assumption is the mother of all mistakes

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What you need to teach yourself

- Ability to work hard (constant speed)
- Programming
- Report writing
- Explaining things to other people
- Convincing people that your right through persuasive arguments

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Last comments

- Assumptions are important (but handle with care)
- Learn your courses, they are important
- The world is your playground, if you're good enough you can make a lot of money, and make the world a better place

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Questions?

Things you should know about

Software:

- Schematic (Mentor graphics, Cadence, Synopsys, Tanner tools)
- Layout (Mentor graphics, Cadence, Synopsys, Tanner tools)
- Simulation (Eldo, Spectre, Hspice, SMASH)
- Scripting (Bash, Perl, Python, TCL, LISP)
- Editors (Emacs)
- Math software (Matlab, Maple, Octave)

Information sources:

- http://ieeexplore.ieee.org
- http://webcast.berkeley.edu/
  - EE240 spring 2007 to spring 2010

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